

THE CIRCUMGALACTIC MEDIUM OF SUBMILLIMETER GALAXIES. I. FIRST RESULTS FROM A RADIO-IDENTIFIED SAMPLE

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ABSTRACT

We present the first results from an on-going survey to characterize the circumgalactic medium (CGM) of the massive high-redshift galaxies detected as submillimeter galaxies (SMGs). We constructed a parent sample of 163 SMG-QSO pairs with separations less than $\sim 36''$ by cross-matching far-infrared-selected galaxies from *Herschel* with spectroscopically confirmed QSOs. The *Herschel* sources were selected to match the properties of SMGs. We determined the sub-arcsecond positions of six *Herschel* sources with the Very Large Array and obtained secure redshift identification for three of those with near-infrared spectroscopy. The QSO sightlines probe transverse proper distances of 112, 157, and 198 kpc at foreground redshifts of 2.043, 2.515, and 2.184, respectively, which are comparable to the virial radius of the $\sim 10^{13} M_{\odot}$ halos expected to host SMGs. High-quality absorption-line spectroscopy of the QSOs reveals systematically strong H I Ly α absorption around all three SMGs, with rest-frame equivalent widths of $\sim 2-3 \text{ \AA}$. However, none of the three absorbers exhibits compelling evidence for optically thick H I gas or metal absorption, in contrast to the dominance of strong neutral absorbers in the CGM of luminous $z \sim 2$ QSOs. The low covering factor of optically thick H I gas around SMGs tentatively indicates that SMGs may not have as prominent cool gas reservoirs in their halos as the co-eval QSOs and that they may inhabit less massive halos than previously thought.

Keywords: galaxies: halos — quasars: absorption lines — intergalactic medium

1. INTRODUCTION

The first milli-Jansky-level submillimeter surveys discovered a population of distant submillimeter-bright galaxies (SMGs), namely, unresolved sources with $850 \mu\text{m}$ flux density (S_{850}) greater than 3–5 mJy (Smail et al. 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999). The SMGs selected at wavelengths between $850 \mu\text{m}$ and 1 mm are intense starbursts ($\text{SFR} \gtrsim 500 M_{\odot} \text{ yr}^{-1}$) at a median redshift of $z \sim 2.5$ (Chapman et al. 2005; Wardlow et al. 2011; Yun et al. 2012; Smolčić et al. 2012). The intense star formation is dust-enshrouded so that the SMGs radiate most of their bolometric luminosity in the far-infrared (IR). The observed molecular and stellar emission indicates that they

are massive gas-rich galaxies ($M_{\text{gas}} \sim M_{\text{star}} \sim 10^{11} M_{\odot}$; e.g., Michałowski et al. 2010; Hainline et al. 2011; Bothwell et al. 2013), but the typical halo mass of SMGs remains uncertain, with estimates ranging from 10^{12} to $10^{13} M_{\odot}$. Two lines of evidence suggest that SMGs may inhabit dark matter halos as massive as $\sim 10^{13} M_{\odot}$: (1) their strong clustering strength estimated from either the angular two-point correlation function (e.g., Scott et al. 2006; Weiß et al. 2009) or the cross-correlation function between SMGs and other high-redshift galaxies (e.g., Hickox et al. 2012), and (2) their high stellar mass and the $M_{\text{star}}-M_{\text{halo}}$ relation from abundance matching ($M_{\text{halo}} = 6 \times 10^{12} M_{\odot}$ for $M_{\text{star}} = 10^{11} M_{\odot}$ at $z = 2$; e.g., Behroozi et al. 2010). However, because source blending due to the large beams of single-dish (sub)millimeter telescopes may have significantly elevated clustering strength (Cowley et al. 2016) and the stellar mass estimates remain uncertain within an order of magnitude (e.g., Hainline et al. 2011; Michałowski et al. 2012; Targett et al. 2012), it is possible that a typical SMG may inhabit much less massive halos ($\sim 10^{12} M_{\odot}$).

SMGs are absent in the local universe and it is commonly thought that they have evolved into the massive ellipticals today (e.g., Blain et al. 2004; Toft et al. 2014). To understand the evolution of SMGs, it is imperative to know how long the observed intense star formation would last. For $10^{13} M_{\odot}$ halos at $z = 2.5$, the average baryonic accretion rate from the mass growth rate of dark matter haloes is $\dot{M}_{\text{gas}} \equiv 0.18 \times \dot{M}_{\text{halo}} \simeq 1.4 \times 10^3 M_{\odot} \text{ yr}^{-1}$ (Neistein & Dekel 2008; Bouché et al. 2010). In such massive halos, it is expected that most of the baryons will be shock-heated to the virial temperature of the halo ($\sim 10^7 \text{ K}$) so that only a small fraction of the accreted gas can actually cool and accrete onto galaxies (e.g., Keres et al. 2005; Dekel & Birnboim 2006). Therefore, the ongoing gas accretion is unlikely to sustain the extreme SFRs. Without a comparable gas supply rate, the SFR would decline

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Table 1
VLA-observed *Herschel* Sources

Pair Name (1)	RA ₂₅₀ (deg) (2)	Dec ₂₅₀ (deg) (3)	S ₂₅₀ (mJy) (4)	S ₃₅₀ (mJy) (5)	S ₅₀₀ (mJy) (6)	Int Time (min) (7)	RA _{6GHz} (deg) (8)	Dec _{6GHz} (deg) (9)	S _{6GHz} ^{peak} (μJy/bm) (10)	S _{6GHz} ^{int} (μJy) (11)
HeLMS 0015+0404	3.9286	+4.0715	61.7±6.0	67.8±5.7	54.3±7.2	26.5	3.93038	+4.07262	69.4±6.7	72.4±13.4
HeLMS 0041-0410	10.3541	-4.1679	80.8±6.2	83.0±6.5	43.6±7.0	15.8	...	...	<35.1	...
L6-XMM 0223-0605	35.8056	-6.0860	33.8±2.3	40.3±2.5	24.2±3.5	69.7	...	...	<14.4	...
G09 0918-0039	139.6159	-0.6644	41.1±6.9	49.7±8.1	31.2±9.1	18.9	...	...	<17.7	...
G09 0920+0024	140.2475	+0.4049	35.0±7.0	51.6±8.1	32.0±8.9	22.9	...	...	<18.6	...
NGP 1313+2924	198.4530	+29.4126	59.7±5.6	78.5±6.6	53.6±7.8	17.2	...	...	<42.3	...
NGP 1330+2540	202.5866	+25.6749	49.2±5.8	54.3±6.4	29.3±7.8	18.0	...	...	<15.3	...
NGP 1333+2357	203.3743	+23.9592	30.4±5.4	31.8±6.4	29.1±7.5	55.2	203.37514	+23.95909	20.0±3.0	31.0±8.1
NGP 1335+2805	203.9409	+28.0986	41.7±5.5	49.8±6.4	38.2±7.7	27.6	203.94249	+28.09750	38.3±4.5	51.4±11.0
G15 1413+0058	213.4580	+0.9725	46.6±6.4	52.8±7.7	36.1±8.5	16.2	213.45743	+0.97321	37.3±5.8	37.3±11.6
G15 1435+0110	218.9043	+1.1682	63.0±6.7	63.8±8.0	56.6±8.8	9.2	218.90494	+1.16958	75.6±7.3	89.1±16.0
G15 1450+0026	222.6773	+0.4351	47.5±6.9	47.9±8.1	29.1±8.9	16.3	...	...	<18.0	...
L6-FLS 1712+6001	258.0352	+60.0281	32.3±2.2	34.0±2.4	22.4±3.6	30.1	258.03111	+60.02722	10.8±2.1	10.8±4.2
							258.04010	+60.02625	13.9±2.1	15.6±4.5

Note. — L6-FLS 1712+6001 has two radio counterparts (see Fig. 1); the first line shows the nominal counterpart, which is closer to the *Herschel* position although slightly fainter. Columns (2-6) list the *Herschel* 250 μm positions and the photometry at 250, 350, and 500 μm. Column (7) is the total VLA on-source integration time. Columns (8-9) list the positions of the radio counterparts. Columns (10-11) are the peak flux density in μJy/bm and the integrated flux density in μJy, both of which are derived by fitting an elliptical Gaussian model to the source. The uncertainty of peak flux density is given by the rms noise in the map at the source position, while the uncertainty of the integrated flux density is estimated using the formulae provided by Hopkins et al. (2003), which includes the 1% uncertainty in the VLA flux-density scale at 6 GHz (Perley & Butler 2013).

with an e -folding timescale of only ~ 200 Myr ($2M_{\text{gas}}/\text{SFR}$; e.g., Greve et al. 2005; Tacconi et al. 2008; Ivison et al. 2011; Bothwell et al. 2013; Fu et al. 2013). At such a rate, the SMGs would become red sequence galaxies in only a Gyr or 5 e -folding times¹⁴. Such a short transitional time of a significant high-redshift star-forming population might help explain the rapid build-up of the massive end of the red sequence at $z > 1$ (e.g., Ilbert et al. 2013). Starbursts thus provide an alternative mechanism to the QSO-mode feedback (e.g. Silk & Rees 1998; Di Matteo et al. 2005) to form red and dead galaxies. Note that both mechanisms still require feedback from radio jets (i.e., the maintenance mode; e.g., Fabian 2012; Heckman & Best 2014) to prevent the hot gaseous halo from cooling. On the other hand, if SMGs were in $10^{12} M_{\odot}$ halos, the intense star formation is also unsustainable because the gas accretion rate is only $\sim 110 M_{\odot} \text{ yr}^{-1}$ at $z = 2.5$.

However, could there be enough cool gas in the circumgalactic medium (CGM) around SMGs to fuel a prolonged starburst phase (e.g. see the simulation of Narayanan et al. 2015)? The CGM of co-eval QSOs may give us a hint, because they inhabit comparably massive ($\sim 10^{12.6} M_{\odot}$) halos (White et al. 2012). Contrary to the expected dominance of virialized X-ray plasma, absorption line spectroscopy of a statistical sample of $z \sim 2$ projected QSO pairs reveals the prevalence of cool ($T \sim 10^4$ K), metal-enriched ($Z \geq 0.1 Z_{\odot}$), and optically thick Ly α absorbers ($N_{\text{HI}} \geq 10^{17.2} \text{ cm}^{-2}$) extending to at least the expected virial radius of 160 kpc (the “QSO Probing QSO” [QPQ] project: Hennawi et al. 2006; Hennawi & Prochaska 2007; Prochaska et al. 2013a,b). The high observed covering factor of the cool CGM gas ($\gtrsim 60\%$) in $\sim 10^{12.6} M_{\odot}$ halos has been compared to predictions from numerical simulations. While several studies found that they cannot reproduce the high covering factor around QSOs (Fumagalli et al. 2014; Faucher-Giguère et al. 2015, but see Rahmati et al. 2015), it has been argued that efficient star-

formation-driven winds from accreted satellite galaxies that interact with cosmological filaments are required to increase the H I covering factor to the observed level, which is only resolved in the highest resolution cosmological zoom simulations (Faucher-Giguère et al. 2016).

These high-resolution simulations predict that the covering factor is roughly independent of SFR, decreases with redshift, and has relatively large halo-halo variations. In the relevant halo mass range, $\sim 3 \times 10^{12} - 10^{13} M_{\odot}$, simulations show H I covering factors of $\sim 30 - 80\%$ with little mass dependence at $z \sim 2$ (Faucher-Giguère et al. 2016). Given the estimated halo masses for QSOs and SMGs, one could expect similar covering factors if these are determined primarily by the interplay between gas infall and star-formation-driven outflows. To test this, we exploit QSO absorption line spectroscopy to probe the CGM of SMGs. We first present the data sets and the method we used to select projected SMG–QSO pairs in § 2. We then describe our followup observations in § 3, including radio interferometer imaging, near-infrared spectroscopy, and optical spectroscopy. We present our analysis and results in § 4, including a comparison between the covering factor of optically thick gas around SMGs and that of $z \sim 2$ QSOs. We summarize the results and conclude in § 5. Throughout we adopt a Λ CDM cosmology with $\Omega_{\text{m}} = 0.27$, $\Omega_{\Lambda} = 0.73$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. SELECTION OF PROJECTED SMG–QSO PAIRS

Because both high-redshift QSOs and SMGs have low number counts, we need large samples of both to come up with a sizable sample of projected SMG–QSO pairs with small angular separations. We compiled 464,866 spectroscopically confirmed QSOs from various surveys: primarily, the Sloan Digital Sky Survey (SDSS; Alam et al. 2015), the 2dF QSO Redshift Survey (2QZ; Croom et al. 2004), the AGN and Galaxy Evolution Survey (AGES; Kochanek et al. 2012), and the MMT Hectospec Redshift Survey of 24 μm Sources in the Spitzer First Look Survey (Papovich et al. 2006). Since we select the foreground galaxies that are likely at $z > 2$ (see the next paragraph), we keep only the 102,472 QSOs at

¹⁴ This is the time it would take to decrease the specific SFR ($\text{SFR}/M_{\text{star}}$) from $\sim 10^{-9} \text{ Gyr}^{-1}$ for the SMGs at the observed epoch to $\sim 10^{-11} \text{ Gyr}^{-1}$ for the red sequence at $z \sim 2$ (Brammer et al. 2009).

$z_{\text{QSO}} > 2.5$. The average surface density of these background QSOs is $\sim 10 \text{ deg}^{-2}$.

To select the foreground SMGs, we combined source catalogs from a number of wide-area extragalactic surveys carried out by the *Herschel*¹⁵ Space Observatory (Pilbratt et al. 2010): the *Herschel* Multi-tiered Extragalactic Survey (HERMES, 95 deg^2 ; Oliver et al. 2012; Wang et al. 2014), the *Herschel* Astrophysical Terahertz Large Area Survey (H-ATLAS, 600 deg^2 ; Eales et al. 2010; Valiante et al. 2016), the *Herschel* Large Mode Survey (HeLMS, 301 deg^2 ; Oliver et al. 2012; Asboth et al. 2016; Nayyeri et al. 2016; ; Clarke et al. in prep.), the *Herschel* Stripe 82 Survey (HerS, 79 deg^2 ; Viero et al. 2014). All of these surveys used SPIRE (Spectral and Photometric Imaging Receiver; Griffin et al. 2010) to image the sky at 250, 350, and 500 μm and the combined xID250¹⁶ catalog contain 1,586,047 sources covering a total of 767 deg^2 (HerS and HeLMS fields overlap by 10 deg^2).

However, most *Herschel* sources are not SMGs; they are, instead, less luminous dusty star-forming galaxies at lower redshifts ($z < 2$; Casey et al. 2012; Casey et al. 2014). To select *Herschel* sources that are likely SMGs, we chose only the subsample that satisfies the following criteria: (1) flux densities peak at 350 μm ($S_{250} < S_{350}$ and $S_{500} < S_{350}$; i.e., “350 μm peakers”), (2) $S_{500} > 20 \text{ mJy}$, and (3) $> 3\sigma$ detections in all three SPIRE bands. Criterion 1 is essentially a photometric redshift selection because emission from dusts at $T = 35 \text{ K}$ would peak at 350 μm if redshifted to $z \sim 2.5$. This is confirmed by the blind carbon monoxide (CO $J = 1-0$) survey of a subsample of the *brightest* 350 μm peakers ($S_{350} \geq 115 \text{ mJy}$), which has shown a strikingly similar redshift distribution as 850 μm -selected SMGs ($z_{\text{CO}} = 2.5 \pm 0.8$; Harris et al. 2012). But note that most of these bright sources are strongly lensed and they do not overlap with our sample. Criterion 2 is introduced to ensure that the Rayleigh-Jeans extrapolation would give $S_{850} > 3 \text{ mJy}$, the classic definition of an SMG, given a typical power-law slope of 3.5 for a modified blackbody with a frequency-dependent absorption cross section ($\kappa \propto \nu^{1.5}$). Criterion 3 ensures that all of the sources we considered are statistically significant. This is necessary because the image depth varies substantially from field to field, ranging from $\sigma_{500} = 15 \text{ mJy beam}^{-1}$ for the large HeLMS and HerS fields (confusion noise included; Oliver et al. 2012; Viero et al. 2014) to confusion limited with $\sigma_{500} = 6.8 \text{ mJy beam}^{-1}$ for the deeper HERMES fields (Nguyen et al. 2010). Given the range of observed far-IR SEDs at $z = 2$ from Casey et al. (2012), our color selection and the high threshold on the 500 μm flux density ensure that $\sim 95\%$ of our sample would be classified as SMGs, if they were observed at 870 μm . Nevertheless, we should keep in mind that the *Herschel*-selected SMGs are a subsample of SMGs and they likely cover a smaller range of dust temperatures than 870 μm -selected SMGs (e.g., Hwang et al. 2010; Magnelli et al. 2012). Only 70,823 *Herschel* sources remained after this selection. The average surface density of 92 deg^{-2} is five times lower than the observed 870 μm source count above $S_{870} \gtrsim 3 \text{ mJy}$ ($\sim 500 \text{ deg}^{-2}$; Weiß et al. 2009; Coppin et al. 2006). This is

not surprising given that almost half of the total *Herschel* area is only 10-20% complete at $S_{500} = 20 \text{ mJy}$. Note that this incompleteness in the *Herschel* catalogs is not a concern for compiling a sample of SMG–QSO pairs.

We identified 230 projected SMG–QSO pairs with angular separations (θ_{250})¹⁷ between $5'' \leq \theta_{250} \leq 36''$ by cross-matching the QSO and SMG subsamples described above. The corresponding impact parameters (R_{\perp}) are between $40 < R_{\perp} < 300 \text{ kpc}$ for $z_{\text{SMG}} = 2.5$. The impact parameter is defined as the transverse proper distance at the redshift of the foreground SMG, which equals the angular diameter distance of the SMG multiplied by the angular separation on sky ($R_{\perp} = D_A(z) \times \theta$). These QSO sightlines thus probe out to ~ 1.5 virial radii of $10^{13} M_{\odot}$ halos ($r_{\text{vir}} = 200 \text{ kpc}$ at $z = 2.5$). Given the positional uncertainty of the *Herschel* 250 μm sources ($\sigma_{\text{pos}} = 3.4''$; see § 4.1), the $5''$ lower limit on the angular separation is imposed as an attempt to avoid far-IR-luminous QSOs, i.e., the QSOs are the SMGs themselves. Through visual inspection of the QSO spectra, we further excluded 31 pairs whose QSOs exhibit strong broad absorption lines (BALs; this makes them unsuitable for absorption line work), have wrong redshifts, or are misclassified. Therefore, our final sample includes 199 pairs, among which 90/163 QSOs have SDSS $g \leq 21/22$ (bright enough for absorption line spectroscopy). One *Herschel* source is probed by two QSOs at $\theta_{250} = 8.0''$ and $18.2''$. No QSO probes multiple *Herschel* sources within $36''$, but a “single” *Herschel* source may consist of multiple SMGs due to the large beam size; so it is possible that a single QSO could probe multiple SMGs at different impact parameters (this is indeed the case for the last source shown in Fig. 1).

3. FOLLOWUP OBSERVATIONS

Extensive followup observations are needed to perform the absorption-line analysis of SMGs. Identifying the absorption features in the spectrum of the background QSO requires a precise redshift for the foreground SMG. But the full-width-at-half-maximum (FWHM) angular resolution of *Herschel* — $18''/25''/36''$ at 250/350/500 μm — precludes longslit spectroscopic observations with typical slit width of $1''$. To obtain more accurate positions and to identify blended sources, we exploit interferometer observations with the Karl G. Jansky Very Large Array (VLA). Furthermore, once the positions are determined with sub-arcsec accuracy, we need to determine the spectroscopic redshifts of the SMGs with near-IR spectrographs by targeting rest-frame optical lines that suffer less dust extinction than rest-frame UV lines. Finally, a high S/N optical/near-UV spectrum of the background QSO is needed to detect the UV absorption lines imprinted by the diffuse medium around the SMGs. Below we describe these observations in more details.

3.1. SMG Identification with the VLA

Far-IR-luminous galaxies like our *Herschel* sources are expected to be luminous in the radio wavelengths, according to the IR-radio correlation (Helou et al. 1985; Condon 1992; Ivison et al. 2010). We can thus obtain better positions for the *Herschel* sources by identifying the radio counterparts with interferometers. We observed 15 SMG–QSO pairs with the VLA in the B configuration with the C-band (6 GHz) receivers (program ID: 15A-266). The sample was selected

¹⁵ *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

¹⁶ 250, 350 and 500 μm fluxes were all extracted at source positions detected on the 250 μm map (e.g., Roseboom et al. 2010; Rigby et al. 2011).

¹⁷ θ_{250} is measured between the *Herschel* 250 μm position and the optical position of the QSO.

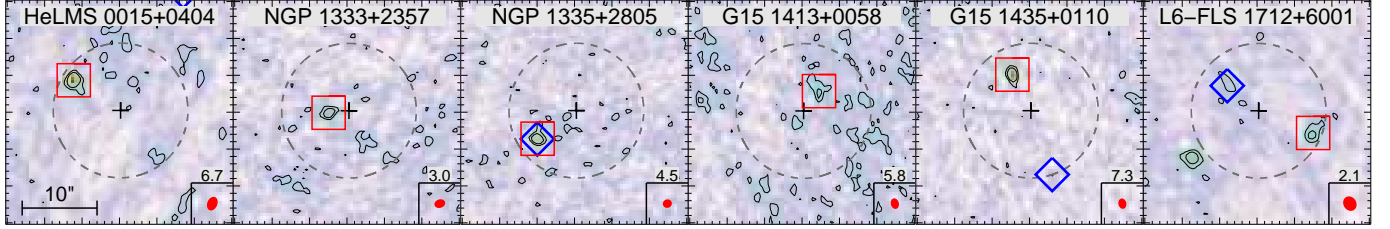


Figure 1. VLA 6 GHz continuum maps for the six VLA-identified SMGs. Each image is $30'' \times 30''$ centered on the *Herschel* position. The restoring beam of each map is plotted as the red ellipse at the lower right corner, above which the 1σ noise level is labeled in units of $\mu\text{Jy beam}^{-1}$. The cross and the dashed circle indicate the *Herschel* positions and the $18''$ FWHM of the $250 \mu\text{m}$ PSF. The red square highlights the detected radio source within the *Herschel* FWHM. The blue diamond marks the optical position of the QSO, if it is within the displayed region. The contours are at $(+2, +4)\sigma$ ($\sigma = 4.9 \mu\text{Jy beam}^{-1}$). Major tickmarks are spaced in $5''$ intervals. N is up and E is left for all panels.

randomly from the SMG–QSO pairs with QSOs brighter than $g \leq 21$, excluding those with $\theta_{250} > 30''$. We later realized that two of the VLA targets in the HeLMS field are likely spurious detections because of Galactic cirrus (Clarke et al. in prep.), so we excluded them in this discussion. Table 1 lists the *Herschel* positions and photometry of the final VLA sample. The receivers have a total bandwidth of 4 GHz at a central frequency of 5.9985 GHz. The targets were selected from six different extragalactic fields. To maximize the observing efficiency, we grouped the targets with their R.A. into five scheduling blocks (SBs) of 0.8 to 3.1 hours. A nearby unresolved calibrator was observed every ~ 10 min. Depending on the R.A. of the targets, 3C 48, 3C 286, or 3C 295 was observed for bandpass and flux-density calibration. The entire program took 8.3 hrs of VLA time. The on-source integration time ranges from 9 to 70 minutes, allocated based on the 6 GHz flux density estimated from fitting the *Herschel* photometry with the SED template of a well-studied, strongly lensed SMG at $z = 2.3259$ (SMM J2135-0102, aka. the “Eyelash”; Swinbank et al. 2010).

The observations were calibrated using the Common Astronomical Software Applications (CASA) package (McMullin et al. 2007). We used the VLA pipeline to perform basic flagging and calibration. Additional flagging was performed whenever necessary by inspecting the visibility data. We used the self-calibration technique with bright sources within the primary beam to reduce the gain errors for four fields: HeLMS 0015+0404, HeLMS 0041–0410, L6-XMM 0223–0605, and NGP 1313+2924. For imaging and deconvolution, we used the standard CASA task CLEAN with “natural” weighting to achieve the best sensitivity. The resulted restoring beams are on average $1''.5 \times 1''.2$ FWHM. The rms image noise level ranges from 2.1 to $14.1 \mu\text{Jy beam}^{-1}$, with a mean of $6 \mu\text{Jy beam}^{-1}$. This measured noise is consistent with thermal noise using natural weighting of the visibility data, except for maps contaminated by the sidelobes of the strong sources lying far outside the cleaned image.

We will present the results in § 4.1, but here is a summary: The VLA detected six of the 13 SMGs; For one of those, NGP 1335+2805, the QSO at $z = 2.973$ itself is responsible for the IR emission, so we excluded it from subsequent spectroscopic observations.

3.2. Near-IR Spectroscopy of the VLA-detected SMGs

With the VLA positions that are accurate to $\lesssim 0.1''$, we carried out a redshift survey for the five VLA-detected SMGs with near-IR spectrographs. The VLA resolved the *Herschel* source of L6-FLS 1712+6001 into two sources at similar brightness (Fig. 1 last panel). We chose the one closer to the *Herschel* position as the nominal counterpart and have

obtained a deep near-IR spectrum at that location. It is unclear whether the two sources are physically related because the redshift of the other source remains to be determined.

We observed G15 1435+0110, L6-FLS 1712+6001, and NGP 1333+2357 with the LUCI-1 spectrograph (LBT NIR-Spectroscopic Utility with Camera and Integral-Field Unit; Seifert et al. 2003) on the Large Binocular Telescope (LBT) on 2015 Apr 14. We used the 200 l/mm $H+K$ grating at $\lambda_c = 1.93 \mu\text{m}$ and the N1.8 camera ($0''.25$ per pixel) to obtain a spectral range between 1.5 and $2.3 \mu\text{m}$. The $1''$ -wide $4'$ -long slit is centered on the VLA-determined SMG position, and it is aligned with the QSO in each pair to obtain the QSO spectrum simultaneously. The QSO spectrum is bright enough to serve as a useful reference for spatial alignment. The spectral resolution (R) is ~ 940 in H -band and ~ 1290 in K -band. We obtained 32×120 s exposures for each target. Between exposures, we dithered along the slit among six dithering positions distributed within $40''$. Atmospheric transparency varied dramatically during the night and no telluric star was observed. So we used the telluric star observation from the previous night for an approximate telluric and flux calibration.

We observed HeLMS 0015+0404 and G15 1413+0058 with the Gemini near-infrared spectrograph (GNIRS; Elias et al. 2006) in the queue mode (program IDs: GN-2015B-Q-46, GN-2016A-Q-41). We used the cross-dispersing prism with the 31.7 l/mm grating and the short camera to obtain a complete spectral coverage between 0.85 – $2.5 \mu\text{m}$. With the $0''.68$ short slit, the spectral resolution is $R \sim 750$ across all orders. We obtained 14×300 s exposures for HeLMS 0015+0404 on 2015 Aug 9, Aug 12, and Oct 18, and 24×115 s exposures for G15 1413+0058 on 2016 May 20. We dithered by $3''$ along the $7''$ -slit between exposures.

Data reduction was carried out with a modified version of LONGSLIT_REDUCE (Becker et al. 2009) for LUCI-1 by Fuyan Bian (Bian et al. 2010) and a modified version of Spextool (Cushing et al. 2004; Vacca et al. 2003) for GNIRS by Katelyn Allers (private communication). These IDL packages carry out the standard data reduction steps for near-IR spectroscopy: flat-fielding, wavelength calibration, pairwise sky subtraction, residual sky removal, shifting and coadding, spectral extraction, telluric correction, and flux calibration.

We identified narrow emission lines in three of the five observed SMGs, which enabled redshift measurements. We were unable to determine the redshifts of the other two sources because we detected only the continuum emission at low S/N.

3.3. Optical Spectroscopy of the Background QSOs

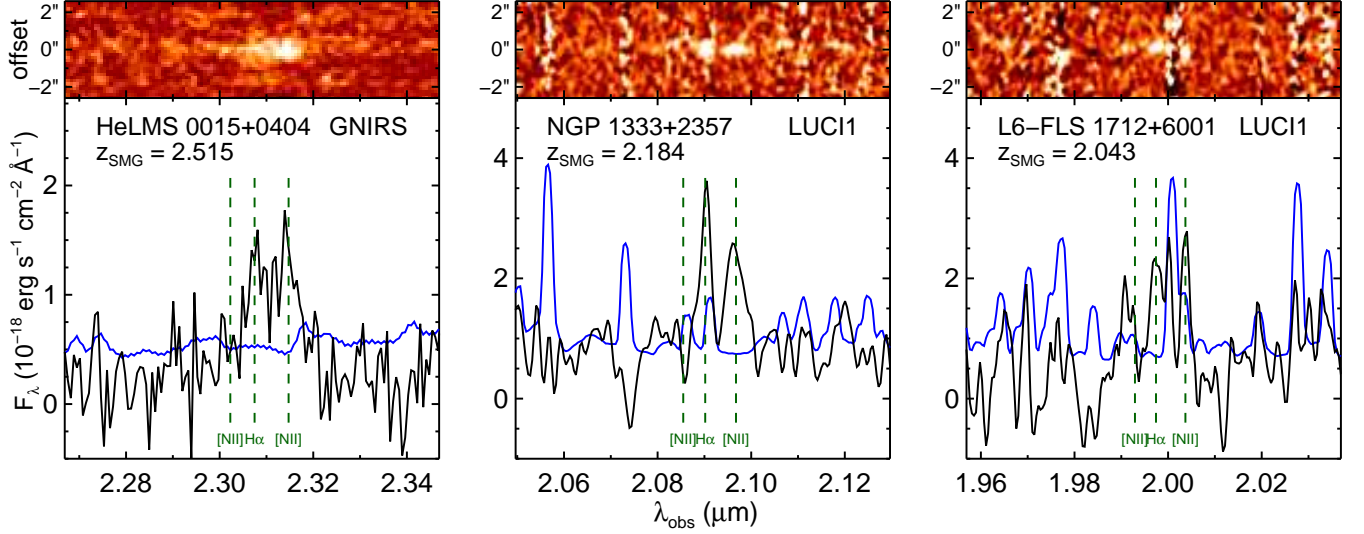


Figure 2. Near-infrared spectra of the VLA-identified SMGs. The top panel shows the coadded 2D spectrum. The ordinate is the positional offset along the spatial direction, and is centered on the SMG location. The bottom panel shows the flux-calibrated 1D spectrum (black) and its 1σ uncertainty (blue). Wavelengths affected by strong sky lines show large errors. The dashed lines indicate the redshifted H α λ 6563 and [N II] λ 6548,6583 lines.

Although previous optical spectra exist for all of the QSOs in our sample, most of them do not have the necessary wavelength coverage or sufficient S/N for absorption line analysis. Hence we obtained new optical spectra for the three background QSOs that are associated with the spectroscopically identified SMGs. We observed HeLMS 0015+0404 and NGP 1333+2357 on 2016 Jan 9 and L6-FLS 1712+6001 on 2015 Jun 13 with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I telescope. We used the $1''$ longslit and the 560 Dichroic for both runs. For the former run, we used the 600/4000 Grism on the blue side ($R \sim 1000$ at $4,000 \text{ \AA}$, $\text{FWHM} = 300 \text{ km s}^{-1}$) and the 600/7500 grating at $\lambda_c = 7,407 \text{ \AA}$ on the red side to cover from $3,300$ to $8,700 \text{ \AA}$. For the latter run, we used the 400/3400 Grism on the blue side ($R \sim 600$ at $4,000 \text{ \AA}$, $\text{FWHM} = 500 \text{ km s}^{-1}$) and the 400/8500 grating tilted to a central wavelength of $\lambda_c = 8,300 \text{ \AA}$ on the red side to cover from $3,300$ to $10,200 \text{ \AA}$. The total integration time for each source ranged between 30 min and 40 min. Conditions were non-photometric for both nights. We obtained useful spectra for all three background QSOs.

We reduced the raw data with XIDL, an IDL data reduction package for a number of spectrographs written by two of us (JXP and JFH). The pipeline follows the standard data reduction steps and reduces the blue and red channels separately. It begins by subtracting a super bias from the raw CCD frames, tracing the slit profiles using flat fields, and deriving the 2D wavelength solution for each slit using the arcs. Then it flat-fields each slit and rejects cosmic-rays, identifies objects automatically in the slit, and builds the bspline super sky model without rectification (Kelson 2003). After subtracting the super sky model, it performs optimal 1D extraction based on the spatial profile of the QSO (Horne 1986). Finally, it removes instrument flexure using isolated sky lines, performs heliocentric correction, and does flux calibration.

4. RESULTS

4.1. Radio Detections

We targeted the *Herschel* sources in 13 SMG–QSO pairs with the VLA and made six clear detections (46%

detection rate). Figure 1 shows the VLA detections and Table 1 lists the 6 GHz positions and flux density measurements for the detections and 3σ upper limits on the non-detections. The VLA revealed five genuine SMG–QSO pairs (HeLMS 0015+0404, NGP 1333+2357, G15 1413+0058, G15 1435+0110, L6-FLS 1712+6001) and one far-IR-luminous QSO (NGP 1335+2805).

The VLA-detected SMGs have 6 GHz peak flux densities between 11 and $76 \mu\text{Jy}$ with a mean of $\sim 40 \mu\text{Jy}$. For these detections, there is a clear positive correlation between the observed flux densities at 6 GHz and $500 \mu\text{m}$, as expected from the IR-radio correlation convolved with a redshift distribution. The 54% non-detection rate is not surprising given the uncertainties in the predicted 6 GHz flux density and the fact that the sensitivity of radio data may deviate substantially from the theoretical prediction because of confusion sources and weather.

The offsets between the *Herschel* positions and the VLA positions range between $2.7''$ and $7.9''$. The maximum offset is comparable to the estimated 2σ positional uncertainty of *Herschel* 250 μm -selected catalogs: $\sigma_{\text{pos}} = \sqrt{2}\sigma_{\text{R.A.}} = 0.93 \times \text{FWHM}/\text{SNR} = 3.4''$ for $\text{FWHM} = 18.1''$ and $\text{SNR} = 5$ (Ivison et al. 2007; Smith et al. 2011). This indicates that a fraction of the “pairs” that have small angular separations ($\theta_{250} \lesssim 8''$) could be single sources, i.e., QSOs that are far-IR-luminous. In our VLA-detected sample, NGP 1335+2805, with $\theta_{250} = 6.5''$, is the only such case (see the third panel of Fig. 1). The VLA position agrees with the optical QSO position within $0.1''$, which is well within the cross-band astrometry accuracy of $\sim 0.3''$ (SDSS+VLA; e.g., Ivezić et al. 2002). But on the other hand, the SMG in L6-FLS 1712+6001 is a separate source from the QSO, despite its even smaller 250 μm separation ($\theta_{250} = 5.4''$). We thus chose not to exclude pairs with $5'' < \theta_{250} < 8''$. The far-IR-luminous QSOs in our sample are interesting on their own right and they will be discussed elsewhere.

4.2. Physical Properties of the SMGs

Estimating the intrinsic properties of the VLA-detected *Herschel* sources require knowledge of their spectroscopic redshifts. We obtained deep near-IR spectra for the five

Table 2
Properties of the Spectroscopically Confirmed SMG–QSO pairs

Pair Name	SMG (J2000)	z_{SMG}	$\log(L_{\text{IR}})$ (L_{\odot})	q_{IR}	QSO (J2000)	z_{QSO}	$\theta_{6\text{GHz}}$ ($''$)	R_{\perp} (kpc)	$W_{\text{Ly}\alpha}$ (Å)	Optical Depth Classification
HeLMS 0015+0404	J001543.29+040421.4	2.515	13.1	2.1	J001542.31+040433.5	3.256	19.0	157	2.0 ± 0.2	ambiguous
NGP 1333+2357	J133330.03+235732.7	2.184	12.6	2.3	J133330.36+235709.9	3.108	23.3	198	1.7 ± 0.2	ambiguous
L6-FLS 1712+6001	J171207.47+600138.0	2.043	12.6	2.6	J171209.00+600144.4	2.821	13.1	112	2.9 ± 0.5	optically thin

VLA counterparts whose spectroscopic redshifts are previously unknown. We detected $\text{H}\alpha$ and $[\text{N II}]$ lines from three of the five sources, enabling accurate determination of the spectroscopic redshifts (Fig. 2 and Table 2). The $[\text{N II}]/\text{H}\alpha$ line ratios are consistent with the range observed in typical SMGs ($0.1 \lesssim [\text{N II}]/\text{H}\alpha \lesssim 1.4$; Swinbank et al. 2004). The two remaining sources, G15 1413+0058 and G15 1435+0110, show near-IR continuum emission without detectable emission lines or stellar absorption features. It is possible that the emission lines either fall into one of the telluric absorption bands or are simply outside of the spectral range. Our redshift success rate is thus 60%, comparable to previous redshift surveys of SMGs in the optical (e.g., Chapman et al. 2005; Casey et al. 2011).

With the photometry from *Herschel* and the VLA and spectroscopic redshifts, we can estimate the total rest-frame 8–1000 μm luminosity (L_{IR}) and the IR-to-radio luminosity ratio (q_{IR}). The results are listed in Table 2. We fit the *Herschel* photometry with a modified blackbody at the spectroscopic redshift, with β fixed to 1.5. We find that they have $L_{\text{IR}} > 10^{12} L_{\odot}$ and $\text{SFR}_{\text{IR}} = 470\text{--}1500 M_{\odot} \text{ yr}^{-1}$. The SFR is estimated from L_{IR} using the calibration of Murphy et al. (2011) for a Kroupa (2002) initial mass function:

$$\text{SFR}/M_{\odot} \text{ yr}^{-1} = 1.5 \times 10^{-10} L_{\text{IR}}/L_{\odot}. \quad (1)$$

The extrapolated 850 μm flux densities range between $7 \leq S_{850} \leq 18 \text{ mJy}$, confirming that they are SMGs.

The IR-to-radio luminosity/flux ratio is estimated using the following equation (Helou et al. 1985; Ivison et al. 2010):

$$q_{\text{IR}} = \log \frac{S_{\text{IR}}/3.75 \times 10^{12} \text{ W m}^{-2}}{S_{1.4\text{GHz}}/\text{W m}^{-2} \text{ Hz}^{-1}} \quad (2)$$

where S_{IR} is rest-frame integrated 8–1000 μm flux and $S_{1.4\text{GHz}}$ is the rest-frame 1.4 GHz flux density¹⁸. The former is from the modified blackbody fit to the IR SED, and the latter is converted from the observed 6 GHz flux densities assuming a typical synchrotron slope ($S_{\nu} \propto \nu^{-0.8}$). The three SMGs show $2.1 \leq q_{\text{IR}} \leq 2.6$, consistent with the observed radio-IR correlation for *Herschel* sources ($q_{\text{IR}} = 2.4 \pm 0.5$; Ivison et al. 2010). This indicates that our sample is not biased to radio-loud AGNs despite being radio selected.

4.3. Absorption Line Systems

To compare with previous work on the CGM of other high-redshift galaxies, we need to characterize the covering factor of optically thick gas clouds around SMGs (i.e., Lyman Limit Systems [LLSs] with column densities of neutral hydrogen $N_{\text{HI}} > 10^{17.2} \text{ cm}^{-2}$). We search for $\text{Ly}\alpha$ absorbers near the spectroscopic redshifts of the foreground SMGs and classify

the $\text{Ly}\alpha$ absorbers in the QSO spectra following the procedure used in the QPQ study (e.g., Prochaska et al. 2013a). We classify the absorbers as optically thick (i.e., LLSs), optically thin, or ambiguous based on the $\text{Ly}\alpha$ equivalent widths (EWs) and the presence of associated metal transitions.

We first identify H I $\text{Ly}\alpha$ absorption due to the SMGs in the QSO spectra within $\pm 600 \text{ km s}^{-1}$ of the systemic redshifts of the SMGs. The search window is chosen because the escape velocity is 610 km s^{-1} at the virial radius ($R_{\text{vir}} = 230 \text{ kpc}$) of a $10^{13} M_{\odot}$ dark matter halo at $z = 2$ (Navarro et al. 1996; Bullock et al. 2001). Strong $\text{Ly}\alpha$ absorption lines are detected in all three systems (Fig. 3). We report their rest-frame EWs ($W_{\text{Ly}\alpha}$), updated angular separations based on the VLA positions ($\theta_{6\text{GHz}}$), and the impact parameters (R_{\perp}) in Table 2. As we have found in our earlier QSO absorption line studies, systematic error associated with continuum placement and line blending generally dominates the statistical error of the QSO spectra. So we estimate the error of $W_{\text{Ly}\alpha}$ assuming 10% error in the continuum placement. From our best-fit Gaussians to the absorption profiles (shown in Fig. 3), we find that all three systems show strong $\text{Ly}\alpha$ absorption lines with $W_{\text{Ly}\alpha} = 1.7\text{--}2.9 \text{ Å}$. Note that when $z_{\text{QSO}} - z_{\text{SMG}} \gtrsim 0.5$, the H I $\text{Ly}\alpha$ absorption from the SMG may lie within the QSO $\text{Ly}\beta$ forest. Unfortunately, all three pairs fall in this category, so contamination from $\text{Ly}\beta$ lines from systems in the $\text{Ly}\alpha$ forest may be a concern. However, it turned out that $\text{Ly}\beta$ contamination is not a serious issue for these systems. Because assuming the detected $\text{Ly}\alpha$ absorption to be $\text{Ly}\beta$, we searched for the corresponding $\text{Ly}\alpha$ lines in each spectrum but did not find any.

Given the absorption profiles of the $\text{Ly}\alpha$ line, we then searched for the associated metal transitions commonly observed in optically thick absorption systems (e.g., Prochaska et al. 2015): Si II $\lambda 1260, 1304, 1527$, O I $\lambda 1302$, C II $\lambda 1335$, Si IV $\lambda 1394, 1403$, C IV $\lambda 1548, 1551$, Fe II $\lambda 1608, 2383, 2600$, Al II $\lambda 1671$, and Mg II $\lambda 2796, 2804$. However, none of these metal transitions is convincingly detected in any of our systems. In the following, we discuss the systems individually and provide our classifications:

- *HeLMS 0015+0404*. This system shows an H I $\text{Ly}\alpha$ absorption at $+500 \text{ km s}^{-1}$ with $W_{\text{Ly}\alpha} = 2.0 \pm 0.2 \text{ Å}$ and *intrinsic*¹⁹ FWHM = 430 km s^{-1} (Fig. 3 *top panels*). The equivalent width gives an upper limit on the H I column density at $\log(N_{\text{HI}}) \lesssim 18.9 \pm 0.1 \text{ cm}^{-2}$. The column density is estimated from the theoretical curve of growth where $W_{\text{Ly}\alpha} = 7.3 (N_{\text{HI}}/10^{20} \text{ cm}^{-2})^{0.5} \text{ Å}$ for $N_{\text{HI}} > 10^{18} \text{ cm}^{-2}$, the regime where the relation is insensitive to the Doppler b -parameter (e.g., Mo et al. 2010, §16.4.4). This is an upper limit because it assumes that the absorption is dominated by a single component,

¹⁸ This flux ratio is equivalent to the luminosity ratio defined in Kovács et al. (2006).

¹⁹ Instrumental broadening has been deconvolved.

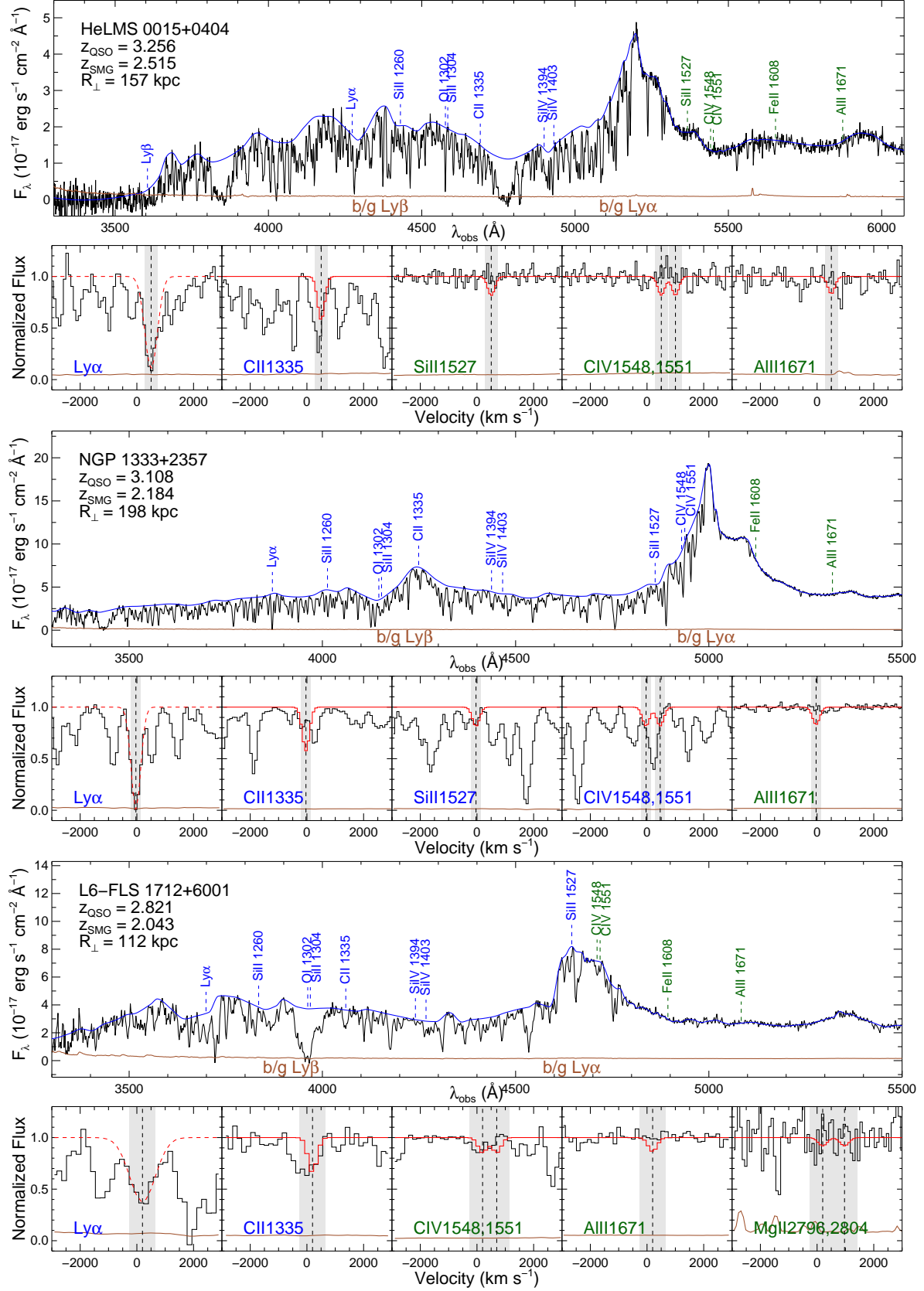


Figure 3. Keck optical spectra of background (b/g) QSOs probing foreground SMGs. The black curve shows the observed flux-calibrated spectrum, while the blue curve shows the continuum model used to normalize the spectrum. The expected locations of absorption lines due to the foreground SMG are marked in blue and green for lines inside and outside the Lyman forests, respectively. Below the full spectrum, we also show the velocity profiles for the H I Ly α and a number of common metal absorption lines. All panels show the region $\pm 3000 \text{ km s}^{-1}$ around the systemic redshifts of the foreground SMGs. In the first panel, we show a Gaussian fit to the strongest H I Ly α absorption line within our search window of $\pm 600 \text{ km s}^{-1}$. In other panels, we overlay the metal line profiles of a typical LLS, using the average observed EWs (0.6 Å for C II and 0.3 Å for other lines; Prochaska et al. 2013b). The vertical dashed line shows the centroid velocity and the gray shaded region highlights the $\pm 1\sigma$ width of the best-fit Gaussian. Both components of the C IV and Mg II doublets are highlighted.

while line blending is likely in the forest. There is putative C II absorption at $+400 \text{ km s}^{-1}$ ($W_{\text{CII}} = 1.2 \text{ \AA}$); but it is likely a false identification of a Ly α forest line, because it is misaligned in velocity with the Ly α absorption and none of the strong metal lines in the “clean” region outside of the Lyman forests is detected (e.g., Si II, C IV, Fe II, Al II). To assess our sensitivity to these strong metal lines in a typical LLS, we have overlaid the expected absorption profiles on top of the observed spectra in Fig. 3. The model absorption lines are smoothed to the spectral resolution and have the average EWs in LLSs around $z \sim 2$ QSOs: 0.6 \AA for C II and 0.3 \AA for the other lines (Prochaska et al. 2013b). It is clear that the S/N of our spectra are high enough to detect the metal lines from a typical LLS when the lines lie outside of the Lyman forest. Without detections of strong metal lines and/or the damping wings in Ly α , we cannot conclude that the absorber is optically thick based on current data because the high $W_{\text{Ly}\alpha}$ could be due to line blending. We conservatively classify this system as ambiguous, even though the non-detection of strong metal lines strongly suggests that it is an optically thin absorber, because fewer than 5% of optically thick absorbers have no detection of a metal transition (Prochaska et al. 2015).

- *NGP 1333+2357*. This system shows an H I Ly α absorption at -34 km s^{-1} with $W_{\text{Ly}\alpha} = 1.7 \pm 0.2 \text{ \AA}$ and intrinsic FWHM = 260 km s^{-1} (Fig. 3 *middle panels*). Similar to HeLMS 0015+0404, the equivalent width gives an upper limit on the H I column density at $\log(N_{\text{HI}}) \lesssim 18.8 \pm 0.1 \text{ cm}^{-2}$. We observe putative absorption around the expected locations of C II, Si IV, Si II, and C IV. But all of these lines lie within the Ly α forest, and their velocity profiles are distinctly different from that of the Ly α line, indicating that these putative metal absorption are spurious. The Fe II and Al II lines are outside of the Lyman forests, but the expected absorption lines are not detected. Like the previous case, we conservatively classify this system as ambiguous.
- *L6-FLS 1712+6001*. There is a broad but shallow H I Ly α absorption line at $+200 \text{ km s}^{-1}$ with $W_{\text{Ly}\alpha} = 2.9 \pm 0.5 \text{ \AA}$ and intrinsic FWHM = 950 km s^{-1} (Fig. 3 *bottom panels*). The equivalent width gives an upper limit on the H I column density at $\log(N_{\text{HI}}) \lesssim 19.2 \pm 0.2 \text{ cm}^{-2}$. But this system is most likely optically thin because the line center drops only to $38 \pm 4\%$ of the continuum intensity (i.e., it does not go line black like the other two systems). Applying the instrumental broadening and pixel sampling to theoretical Voigt profiles, we find that the line center depth places a much stronger limit on the H I column density than the equivalent width: $\log(N_{\text{HI}}) \lesssim 17.5 - 15.8$ at $b = 20 - 30 \text{ km s}^{-1}$, the range of b parameters observed in H I absorbers at $z \sim 2 - 3$ (e.g., Hu et al. 1995; Rudie et al. 2012). Like the previous cases, we observe putative metal absorption inside the Lyman forests (e.g., O I, C II, Si II, and Si IV) but no metal absorption outside of the forests (e.g., C IV, Fe II, Al II, and Mg II²⁰). Note that the weak C IV absorption

is blueshifted by more than 200 km s^{-1} from the Ly α line center. Considering the strict limit on the H I column density and the absence of metal lines, we classify this system as optically thin.

In summary, we have identified one clearly optically thin case and two ambiguous cases with three QSO sightlines covering impact parameters between $100 < R_{\perp} < 200 \text{ kpc}$ around SMGs at $2.0 < z < 2.6$. The two ambiguous cases are also likely to be optically thin, given the non-detection of any metal transitions.

4.4. Comparison with the CGM around QSOs

For background QSO sightlines probing the CGM of $z \sim 2 - 3$ foreground QSOs, one observes H I absorbers optically thick at the Lyman limit $\gtrsim 60\%$ of the time. The high H I covering factor extends to at least the expected virial radius of $\sim 160 \text{ kpc}$ (Hennawi et al. 2006; Prochaska et al. 2013a,b). In Figure 4, we compare (1) the SMG sample distribution with the QSOs from the QPQ project, and (2) the covering factor of optically thick H I gas around SMGs with that around QSOs. The two samples overlap in the plane of foreground redshift vs. impact parameter: the SMGs cover the same redshift range as the QSOs in the intermediate impact parameter range between 100 and 200 kpc. We calculate the 1σ binomial confidence intervals of the optically thick fraction using the quantiles of the beta distribution (Cameron 2011). Because there is no clearly optically thick absorber among the three systems we analyzed, our 1σ confidence interval of the covering factor is 4.2–36.9% for a non-detection in a sample of three. For comparison, we consider all of the QSO sightlines with $100 < R_{\perp} < 200 \text{ kpc}$ from the QPQ project (Prochaska et al. 2013a) and we find the optically thick covering factor is $64^{+7}_{-9}\%$ for 21 clearly optically thick systems among 33 systems. Therefore, despite our small sample, the upper bound of our 1σ confidence interval is 3σ below the best-estimated covering factor around QSOs at the same ranges of redshifts and impact parameters.

Note that although our analysis may appear to have limitations based on the classification of two of the SMG absorbers as ambiguous, these same limitations also apply to the QPQ analysis, and are inherent to any attempt to classify absorbers using low or moderate resolution spectra without coverage of the H I Lyman limit (at 912 \AA in the rest-frame). As such, we have followed exactly the same procedure for absorber classification as in the QPQ studies, enabling a direct comparison to that work. Our data have shown that clear optically thick cases appear much less frequently around SMGs than around co-eval QSOs. However, if we were to treat the ambiguous cases in both samples as if they were optically thick absorbers, then the difference in the optically thick covering factor becomes smaller because of the high number of ambiguous cases in the SMG sample: the covering factor around SMGs increases to $67^{+15}_{-28}\%$ (2 out of 3 systems), while the covering factor around $z \sim 2$ QSOs increases to $91^{+3}_{-8}\%$ (30 out of 33 systems) between $100 < R_{\perp} < 200 \text{ kpc}$.

There are some minor differences between our analysis and the QPQ analysis. But they are unlikely to affect our result. First, the bulk of the QPQ dataset (Prochaska et al. 2013b) utilized background QSO spectra with moderate resolution ($R \sim 2000$). This is a factor of two higher than the resolution we used for the QSO spectra probing two of our SMGs

²⁰ Because of the wider spectral coverage and the lower foreground redshift, this is the only object where we have coverage of the Mg II $\lambda 2796, 2804$

($R \sim 1000$), whereas in L6-FLS 1712+6001 our spectrum has $R \sim 600$. But the lower resolution of our spectra does not play a significant role in the resulting classification of our absorbers, since the typical strength of the metal lines seen in the optically thick systems would still be easily detectable at $R \sim 1000$, and the one system that we observed at $R \sim 600$ is most likely optically thin, since it does not go line black. Another significant difference, is whereas Prochaska et al. (2013b) restricted analysis to only those foreground QSOs with redshifts lying within the $\text{Ly}\alpha$ forest of the background QSO, we have included foreground SMGs landing in the $\text{Ly}\beta$ forest, owing to the larger redshift separations between the SMGs and the QSOs in our sample. This is unlikely to impact our deduced covering factor in Fig. 4 though. For example, earlier QPQ studies (Hennawi et al. 2006; Hennawi & Prochaska 2007, 2013) also considered absorbers lying in the $\text{Ly}\beta$ forest, and the covering factor deduced there was consistent with that derived in Prochaska et al. (2013b). Furthermore, in all of the three SMG–QSO pairs shown in Fig. 3, multiple metal lines that are strong in optically thick absorbers (i.e., $\text{Si II } \lambda 1527$, $\text{C IV } \lambda \lambda 1548, 1551$, $\text{Al III } \lambda 1671$, and $\text{Mg II } \lambda \lambda 2796, 2804$) land in the clean regions outside of the Lyman forest but remain undetected. Finally, whereas QPQ searched for absorbers within a velocity window in a $\pm 1500 \text{ km s}^{-1}$ window owing to the large errors in QSO redshifts, we adopted a $\pm 600 \text{ km s}^{-1}$ search window. We were able to consider a smaller velocity interval because our SMG redshifts derived from narrow rest-frame optical lines are much more accurate, and this interval was instead chosen to encompass the typical virial motions in a $10^{13} M_{\odot}$ dark matter halo. The larger velocity interval used in QPQ formally implies a higher level of contamination from physically unassociated absorbers. But the contamination is estimated to be at only $\sim 3\%$ level for a $\pm 1500 \text{ km s}^{-1}$ window (Prochaska et al. 2013b, see their Figure 10 and Table 7). This is too small to be responsible for the difference in the optically thick covering factor that we observe between QSOs and SMGs.

5. SUMMARY AND CONCLUSIONS

Motivated by the unique properties of SMGs and their purported evolutionary link to high-redshift QSOs and today’s massive ellipticals, we have started a project to use QSO absorption line spectroscopy to probe the diffuse cool H I gas in the CGM of SMGs. This work requires a sample of projected SMG–QSO pairs, which are extremely rare. Wide-area sub-millimeter surveys are needed to compile such a sample. Thanks to the advent of *Herschel*, we have identified 163 SMG–QSO pairs with bright $z > 2.5$ QSOs ($g_{\text{QSO}} < 22$) and angular separations between $5''$ and $36''$ from a suite of wide-area *Herschel* surveys and spectroscopic QSO surveys.

Extensive followup observations are required to carry out the absorption line study. To allow slit spectroscopy, the first stage is to use an interferometer to pin down the positions of the *Herschel* sources. This paper focuses on a subsample of 13 SMG–QSO pairs that were observed with the VLA in C-band. With an average integration time of 25 min per source, the VLA detected sources within the *Herschel* beam in six fields. One of the six SMG–QSO pair turns out to be a far-IR-luminous QSO at $z = 2.973$, while the *Herschel* source in another pair turns out to be a pair of SMGs. Hence, we effectively identified six SMG–QSO pairs from observations of 13 fields (46%). The second stage is to measure the spectroscopic redshifts of the SMGs. We observed five of the six

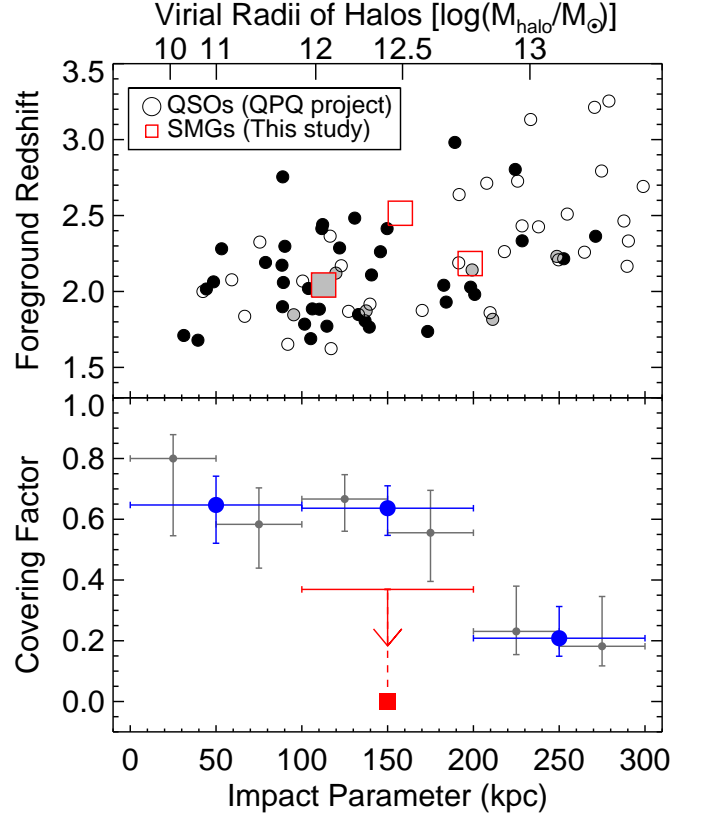


Figure 4. *Top:* Sample distributions in foreground redshift vs. impact parameter. The red squares and the black circles show the SMGs from this study and the QSOs from the QPQ survey (Prochaska et al. 2013a), respectively. The black-filled, gray-filled, and open symbols correspond to systems that are optically thick, optically thin, and ambiguous, respectively. The top axis marks the virial radii for a range of dark matter halos at $z = 2$. *Bottom:* The covering factor of optically thick gas around SMGs (red square with a downward arrow: our 1σ confidence interval for a non-detection in a sample of three) vs. impact parameter, compared to that around QSOs from the QPQ survey (blue/gray circles with error bars; Prochaska et al. 2013a). The blue and gray circles are estimates of the covering factor based on 100 kpc-wide bins and 50 kpc-wide bins, respectively. Our sample probes similar ranges of redshifts and impact parameters as the QPQ QSOs but shows less optically thick absorbers.

VLA-identified SMG–QSO pairs with near-IR spectroscopy. We were able to determine the redshifts for three of the five SMGs (60%) from the redshifted $\text{H}\alpha$ and $[\text{N II}]$ lines. The remaining two sources show only featureless continuum in the near-IR windows, making it impossible to determine an accurate redshift. The last stage is to obtain optical spectroscopy of the QSOs once it is confirmed that the QSOs are in the background of the SMGs. Because we have selected only the brightest QSOs, the success rate of this step is approaching 100%. Because of the low success rates of the first two followup stages, only $\sim 23\%$ of the initial sample (i.e., three SMG–QSO pairs out of 13) are spectroscopically confirmed and are suitable for final absorption line study. Our main findings are as follows:

1. The near-IR spectra of the five VLA-detected sources are all detected in hour-long integrations with 8-meter telescopes, although only three of those show emission lines that yielded accurate spectroscopic redshifts. Since we positioned the slits on the VLA positions, this result shows that the spatial offset, if any, between the near-IR and the radio counterparts is less than an arcsec (the slit width), consistent with the finding from differ-

ential lensing in strongly lensed sources (e.g., Fu et al. 2012).

2. The VLA-identified *Herschel* “350 μ mpeakers” at $2.0 < z < 2.6$ are similar to SMGs selected at longer wavelengths (i.e., 850 μ m to 1 mm), in terms of the [N II]/H α ratio (i.e., gas metallicity), the IR luminosity (i.e., SFR), and the IR-to-radio luminosity ratio (i.e., radio excess due to AGN). The VLA-identified SMGs are optically faint and unbiased to radio-loud AGNs, so they indeed represent a galaxy population distinct from the optical selected QSOs and the Lyman break galaxies (LBGs) in the same redshift range.
3. Strong H I Ly α absorption is found in the background QSO spectra for all of the three spectroscopically confirmed SMG–QSO pairs with impact parameters between $100 < R_{\perp} < 200$ kpc. Here we have adopted a much narrower search window (± 600 km s $^{-1}$) than the QPQ study, further reducing the level of contamination from physically unrelated clouds. However, none of the three absorption line systems seems optically thick at the Lyman limit (i.e., LLSs with $N_{\text{HI}} > 10^{17.2}$ cm $^{-2}$), in contrast to the $\sim 60\%$ covering factor of LLSs around QSOs from the QPQ study despite similar data quality, foreground redshifts, and impact parameters.

Our comparison thus suggests *either* that SMGs do not have a substantial neutral gas reservoir in their halos that could potentially fuel a prolonged star formation phase *or* that SMGs inhabit $\sim 10^{12} M_{\odot}$ halos so that our sightlines are yet to probe inside their virial radii. If the latter, their halos are comparable to those of LBGs. Rudie et al. (2012) found an optically thick covering factor of $30 \pm 14\%$ around LBGs at $z \sim 2.3$ and $R_{\perp} < 90$ kpc. Note that this is $\sim 2\times$ lower than that of coeval QSOs and is consistent with the 1σ confidence interval that we were able to place for the SMGs. On the other hand, the difference in the optically thick H I covering factor between SMGs and QSOs casts doubt on the evolutionary link between the two populations, unless AGN outflows can somehow affect the physical state of gas at hundreds of kpc scales within its short lifetime.

Our final conclusion is limited by the small sample size. To enable a more robust comparison with previous absorption-line studies, we badly need to increase the effective yield of our survey from the current level of $\sim 23\%$. In a future publication, we will present observations with the Atacama Large Millimeter/submillimeter Array (ALMA) to pinpoint the positions of the *Herschel* sources in the SMG–QSO pairs. Observing at a wavelength (870 μ m) much closer to the selection wavelengths (250 to 500 μ m), we expect doubling the detection rate with integration times of just several minutes per source. The *Herschel* sources in our sample are too faint to allow a quick CO redshift search with ALMA (e.g., the survey of strongly lensed SMGs by Weiß et al. 2013), but spectrographs on large optical telescopes covering the full optical+IR range at a moderate spectral resolution ($R \gtrsim 2000$) will greatly increase the redshift search range and decrease the areas blinded by strong airglow lines.

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REFERENCES

- Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, *ApJS*, 219, 12
 Asboth, V., Conley, A., Sayers, J., et al. 2016, *ArXiv e-prints*
 Barger, A. J., Cowie, L. L., Sanders, D. B., et al. 1998, *Nature*, 394, 248
 Becker, G. D., Rauch, M., & Sargent, W. L. W. 2009, *ApJ*, 698, 1010
 Behroozi, P. S., Conroy, C., & Wechsler, R. H. 2010, *ApJ*, 717, 379
 Bian, F., Fan, X., Bechtold, J., et al. 2010, *ApJ*, 725, 1877
 Blain, A. W., Chapman, S. C., Smail, I., & Ivison, R. 2004, *ApJ*, 611, 725
 Bothwell, M. S., Smail, I., Chapman, S. C., et al. 2013, *MNRAS*, 429, 3047
 Bouché, N., Dekel, A., Genzel, R., et al. 2010, *ApJ*, 718, 1001
 Brammer, G. B., Whitaker, K. E., van Dokkum, P. G., et al. 2009, *ApJL*, 706, L173
 Bullock, J. S., Kolatt, T. S., Sigad, Y., et al. 2001, *MNRAS*, 321, 559

- Cameron, E. 2011, *PASA*, 28, 128
- Casey, C. M., Chapman, S. C., Smail, I., et al. 2011, *MNRAS*, 411, 2739
- Casey, C. M., Narayanan, D., & Cooray, A. 2014, *Phys. Rep.*, 541, 45
- Casey, C. M., Berta, S., Béthermin, M., et al. 2012, *ApJ*, 761, 140
- Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, *ApJ*, 622, 772
- Condon, J. J. 1992, *ARA&A*, 30, 575
- Coppin, K., Chapin, E. L., Mortier, A. M. J., et al. 2006, *MNRAS*, 372, 1621
- Cowley, W. I., Lacey, C. G., Baugh, C. M., & Cole, S. 2016, *MNRAS*
- Croom, S. M., Smith, R. J., Boyle, B. J., et al. 2004, *MNRAS*, 349, 1397
- Cushing, M. C., Vacca, W. D., & Rayner, J. T. 2004, *PASP*, 116, 362
- Dekel, A., & Birnboim, Y. 2006, *MNRAS*, 368, 2
- Di Matteo, T., Springel, V., & Hernquist, L. 2005, *Nature*, 433, 604
- Eales, S., Lilly, S., Gear, W., et al. 1999, *ApJ*, 515, 518
- Eales, S. A., Raymond, G., Roseboom, I. G., et al. 2010, *A&A*, 518, L23
- Elias, J. H., Joyce, R. R., Liang, M., et al. 2006, in *Proc. SPIE*, Vol. 6269, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 62694C
- Fabian, A. C. 2012, *ARA&A*, 50, 455
- Faucher-Giguère, C.-A., Feldmann, R., Quataert, E., et al. 2016, *ArXiv e-prints*
- Faucher-Giguère, C.-A., Hopkins, P. F., Kereš, D., et al. 2015, *MNRAS*, 449, 987
- Fu, H., Jullo, E., Cooray, A., et al. 2012, *ApJ*, 753, 134
- Fu, H., Cooray, A., Feruglio, C., et al. 2013, *Nature*, 498, 338
- Fumagalli, M., Hennawi, J. F., Prochaska, J. X., et al. 2014, *ApJ*, 780, 74
- Greve, T. R., Bertoldi, F., Smail, I., et al. 2005, *MNRAS*, 359, 1165
- Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, *A&A*, 518, L3
- Hainline, L. J., Blain, A. W., Smail, I., et al. 2011, *ApJ*, 740, 96
- Harris, A. I., Baker, A. J., Frayer, D. T., et al. 2012, *ApJ*, 752, 152
- Heckman, T. M., & Best, P. N. 2014, *ARA&A*, 52, 589
- Helou, G., Soifer, B. T., & Rowan-Robinson, M. 1985, *ApJ*, 298, L7
- Hennawi, J. F., & Prochaska, J. X. 2007, *ApJ*, 655, 735
- . 2013, *ApJ*, 766, 58
- Hennawi, J. F., Strauss, M. A., Oguri, M., et al. 2006, *AJ*, 131, 1
- Hennawi, J. F., Prochaska, J. X., Burles, S., et al. 2006, *ApJ*, 651, 61
- Hickox, R. C., Wardlow, J. L., Smail, I., et al. 2012, *MNRAS*, 421, 284
- Hopkins, A. M., Afonso, J., Chan, B., et al. 2003, *AJ*, 125, 465
- Horne, K. 1986, *PASP*, 98, 609
- Hu, E. M., Kim, T.-S., Cowie, L. L., Songaila, A., & Rauch, M. 1995, *AJ*, 110, 1526
- Hughes, D. H., Serjeant, S., Dunlop, J., et al. 1998, *Nature*, 394, 241
- Hwang, H. S., Elbaz, D., Magdis, G., et al. 2010, *MNRAS*, 409, 75
- Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, *A&A*, 556, 55
- Ivezić, Ž., Menou, K., Knapp, G. R., et al. 2002, *AJ*, 124, 2364
- Ivison, R. J., Papadopoulos, P. P., Smail, I., et al. 2011, *MNRAS*, 412, 1913
- Ivison, R. J., Greve, T. R., Dunlop, J. S., et al. 2007, *MNRAS*, 380, 199
- Ivison, R. J., Magnelli, B., Ibar, E., et al. 2010, *A&A*, 518, L31
- Kelson, D. D. 2003, *PASP*, 115, 688
- Keres, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, *MNRAS*, 363, 2
- Kochanek, C. S., Eisenstein, D. J., Cool, R. J., et al. 2012, *ApJS*, 200, 8
- Kovács, A., Chapman, S. C., Dowell, C. D., et al. 2006, *ApJ*, 650, 592
- Kroupa, P. 2002, *Science*, 295, 82
- Magnelli, B., Lutz, D., Santini, P., et al. 2012, *A&A*, 539, A155
- McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in *Astronomical Society of the Pacific Conference Series*, Vol. 376, *Astronomical Data Analysis Software and Systems XVI*, ed. R. A. Shaw, F. Hill, & D. J. Bell, 127
- Michałowski, M. J., Dunlop, J. S., Cirasuolo, M., et al. 2012, *A&A*, 541, 85
- Michałowski, M. J., Watson, D., & Hjorth, J. 2010, *ApJ*, 712, 942
- Mo, H., van den Bosch, F. C., & White, S. 2010, *Galaxy Formation and Evolution* (Cambridge University Press)
- Murphy, E. J., Condon, J. J., Schinnerer, E., et al. 2011, *ApJ*, 737, 67
- Narayanan, D., Turk, M., Feldmann, R., et al. 2015, *Nature*, 525, 496
- Nguyen, H. T., Schulz, B., Levenson, L., et al. 2010, *A&A*, 518, L5
- Oke, J. B., Cohen, J. G., Carr, M., et al. 1995, *PASP*, 107, 375
- Oliver, S. J., Bock, J., Altieri, B., et al. 2012, *MNRAS*, 424, 1614
- Papovich, C., Cool, R., Eisenstein, D., et al. 2006, *AJ*, 132, 231
- Perley, R. A., & Butler, B. J. 2013, *ApJS*, 204, 19
- Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, *A&A*, 518, L1
- Prochaska, J. X., Hennawi, J. F., & Simcoe, R. A. 2013a, *ApJL*, 762, L19
- Prochaska, J. X., O'Meara, J. M., Fumagalli, M., Bernstein, R. A., & Burles, S. M. 2015, *ApJS*, 221, 2
- Prochaska, J. X., Hennawi, J. F., Lee, K.-G., et al. 2013b, *ApJ*, 776, 136
- Rahmati, A., Schaye, J., Bower, R. G., et al. 2015, *MNRAS*, 452, 2034
- Rigby, E. E., Maddox, S. J., Dunne, L., et al. 2011, *MNRAS*, 415, 2336
- Roseboom, I. G., Oliver, S. J., Kunz, M., et al. 2010, *MNRAS*, 409, 48
- Rudie, G. C., Steidel, C. C., Trainor, R. F., et al. 2012, *ApJ*, 750, 67
- Scott, S. E., Dunlop, J. S., & Serjeant, S. 2006, *MNRAS*, 370, 1057
- Seifert, W., Appenzeller, I., Baumeister, H., et al. 2003, in *Proc. SPIE*, Vol. 4841, *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes*, ed. M. Iye & A. F. M. Moorwood, 962–973
- Silk, J., & Rees, M. J. 1998, *A&A*, 331, L1
- Smail, I., Ivison, R. J., & Blain, A. W. 1997, *ApJ*, 490, L5
- Smith, D. J. B., Dunne, L., Maddox, S. J., et al. 2011, *MNRAS*, 416, 857
- Smolčić, V., Aravena, M., Navarrete, F., et al. 2012, *A&A*, 548, A4
- Swinbank, A. M., Smail, I., Chapman, S. C., et al. 2004, *ApJ*, 617, 64
- Swinbank, A. M., Smail, I., Longmore, S., et al. 2010, *Nature*, 464, 733
- Tacconi, L. J., Genzel, R., Smail, I., et al. 2008, *ApJ*, 680, 246
- Targett, T. A., Dunlop, J. S., Cirasuolo, M., et al. 2012, *arXiv:1208.3464*
- Toft, S., Smolčić, V., Magnelli, B., et al. 2014, *ApJ*, 782, 68
- Vacca, W. D., Cushing, M. C., & Rayner, J. T. 2003, *PASP*, 115, 389
- Valiante, E., Smith, M. W. L., Eales, S., et al. 2016, *MNRAS*, submitted
- Viero, M. P., Asboth, V., Roseboom, I. G., et al. 2014, *ApJS*, 210, 22
- Wang, L., Viero, M., Clarke, C., et al. 2014, *MNRAS*, 444, 2870
- Wardlow, J. L., Smail, I., Coppin, K. E. K., et al. 2011, *MNRAS*, 415, 1479
- Weiß, A., Kovács, A., Coppin, K., et al. 2009, *ApJ*, 707, 1201
- Weiß, A., De Breuck, C., Marrone, D. P., et al. 2013, *ApJ*, 767, 88
- White, M., Myers, A. D., Ross, N. P., et al. 2012, *MNRAS*, 424, 933
- Yun, M. S., Scott, K. S., Guo, Y., et al. 2012, *MNRAS*, 420, 957